A SYSTEM FOR MONITORING PULMONARY ARTERY PRESSURE IN PATIENTS WITH PULMONARY HYPERTENSION

REFERENCE TO PREVIOUS APPLICATIONS

This application claims the benefit of United States Provisional Applications No. 60/416,406 filed on October 7th, 2002, 60/416,407 filed on October 7th, 2002, 60/416,408 filed on October 7th, 2002, and 60/416,409 filed on October 7th, 2002.

FIELD OF THE INVENTION

The present invention relates generally to field of implantable medical devices for monitoring physiological parameters. More particularly, the invention relates to a system utilizing a telemetric implantable physiologic sensor for diagnosing and/or monitoring the progression of Pulmonary Hypertension and related conditions.

BACKGROUND OF THE INVENTION

The current clinical method for evaluating intracardiac pressures, including those associated with pulmonary hypertension, is a catheterization procedure that requires the patient be admitted to a catheterization lab. Catheterization, however, provides only a snapshot of pressure data, carries morbidity and mortality, and is expensive. Doppler echocardiography is an alternative method for evaluating pulmonary hypertension; however, it too requires specialized equipment in a dedicated laboratory. Following diagnosis of pulmonary hypertension, physicians would prefer to noninvasively monitor this condition on a continuing

basis in order to optimize treatment. The course of patients with PPH (Primary Pulmonary Hypertension) is usually long and chronic. Many treatment modalities have been proposed but none to-date provide an absolute solution. The only way to assess patient response to treatment is by direct invasive measurement of pulmonary artery (PA) pressure. As the disease and treatments are chronic in nature, it will be ideal for the health provider to be able to optimize treatment by continuous monitoring of PA pressure. Currently, no technology exists that has this capability.

SUMMARY OF THE INVENTION

The invention comprises a telemetric sensing system for noninvasively monitoring cardiac physiologic parameters used to evaluate patients with pulmonary hypertension. The system includes an implantable sensor unit and a companion reader unit. The batteryless, wireless pressure sensor unit is chronically implanted in any of several locations in the heart (e.g. right ventricle (RV), right atrium (RA), pulmonary artery (PA)). The implant may be delivered percutaneously (for example, by catheter), surgically, and/or on a stent. Once in place, the implant may be wirelessly interrogated with the reader.

Upon placement in the respective locations in the heart, the implant is capable of measuring and transmitting, in real time, any of various physiologic parameters including RV, RA, PA, and related pressures. This approach would be the preferred way to noninvasively monitor the response of pulmonary artery hypertension to different treatments. Monitoring one or more of these parameters gives the physician several advantages:

- Facilitates earlier intervention in the course of disease
- Enables better tailoring of medications or other treatments and therapies to reduce pulmonary hypertension

- Facilitates the identification of other complications from treatments or disease progression.
- Gives faster feedback on the impact of medications and/or pacing changes on heart function.
- Facilitates pacemaker parameter tuning
- Lowers overall treatment costs
- Decreases frequency and/or severity of hospitalization for pulmonary-hypertension-related conditions through improved outpatient and home care

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic of an implantable pressure monitor anchored in a cavity of the heart.

Figure 2 is a block diagram of a magnetic telemetry based physiologic monitoring system based on a resonant scheme according to a preferred embodiment of the present invention.

Figure 3 is a block diagram of a magnetic telemetry based physiologic monitoring system based on a passive scheme according to an alternate embodiment of the present invention.

Figure 4 is a perspective view of a sensor implant incorporating a screw anchoring mechanism according to a preferred embodiment of the present invention.

Figure 5 is a side view of a sensor implanted in the atrial septum according to a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED AND ALTERNATE EMBODIMENTS OF THE INVENTION

The following description of preferred embodiments and methods provides examples of the present invention. The embodiments discussed herein are merely exemplary in nature, and are not intended to limit the scope of the invention in any manner. Rather, the description of

these preferred embodiments and methods serves to enable a person of ordinary skill in the relevant art to make, use and perform the present invention.

In order to provide for the effective monitoring, management, and tailoring of treatments for pulmonary hypertension, the present invention provides a wireless sensing system. The system comprises an implantable pressure monitor **50** which is securely anchored in a cavity of the heart, as shown in Figure 1, and an external readout unit. The readout unit both transmits power to and receives transmitted data from the implant. Data transmitted from the implantable device may include pressure, temperature, calibration data, identification data, fluid flow rate, chemical concentration, and/or other physiologic parameters. The readout unit may include a barometric pressure sensor in order to compensate for variation in atmospheric pressure.

In the preferred embodiment, the sensor transmits data corresponding to PA, RA, RV, LA (left atrium), LV (left ventricle), dp/dt, and/or the entire RA, PA, RV, LV, or LA waveform can be useful to evaluate pulmonary hypertension. To accomplish this, the sensor is located such that it reads the pressure of interest, typically in the PA, RV, RA, LV or LA as appropriate. Note that the sensor may be located directly in the cavity whose pressure is being monitored, or it may be located in an intermediary structure, such as the atrial or ventricular septum, as long as communication with the parameter of interest is maintained.

The batteryless, wireless telemetry link is preferably implemented using either a resonant or passive, magnetically coupled scheme. A resonant device **101** (shown in Figure 2) is the simplest approach, and consists only of a packaged inductor coil **103** and capacitive pressure sensor **102**. Together, the two elements form a circuit that has a specific resonant frequency. At that resonant frequency, the circuit presents a measurable change in magnetically coupled impedance load to an external coil. Because the resonant frequency is a function of the coil inductance **103** and the sensor capacitance **102,** as pressure changes the

resonant frequency changes as well. An external reader **104** is able to determine pressure by monitoring the frequency at which the coil antenna **105** impedance changes.

The preferred communication scheme for the present invention, shown in Fig. 3, is based on magnetic telemetry. Devices that have on-board circuitry but still receive their operating power from an external source (i.e., are batteryless) are referred to as passive devices **201** (shown in Figure 3). Without an external reader present, the implant device **201** lays passive and without any internal means to power itself. When a pressure reading is desired, the reader device **202** is brought into a suitable range to the implant. In this case the external reader **202** uses an alternating magnetic field to induce a voltage in the implant. When sufficient voltage has been induced in the implant **201**, a rectification circuit **203** converts the alternating voltage on the receiver coil **204** into a direct voltage that can be used by the electronics **205** as a power supply for signal conversion and communication. At this point the implant **201** can be considered alert and, in the preferred embodiment, also ready for commands from the reader. The maximum achievable distance is mostly limited by the magnetic field strength necessary to turn the implant on. This telemetry scheme has been proven and used extensively in the identification and tracking industry (e.g., implantable RF ID technology from Texas Instruments or Digital Angel) with a great deal of acceptance and success.

Once the direct voltage in the implant has been established for the circuit operation, a number of techniques may be used to convert the sensor output into a form suitable for transmission back to the reader device. In the preferred embodiment, a capacitive pressure sensor **206** and sigma delta conversion or capacitance to frequency conversion of the sensor output may be easily used. Capacitive sensors are preferred due to the small power requirements for electronics when reading capacitance values. Many pressure sensors are based on piezoresistive effects and, while suitable for some applications, do suffer in this

application due to the higher power levels needed for readout. Sigma delta converters are preferred due to the tolerance of noisy supply voltages and manufacturing variations.

As those skilled in magnetic telemetry are aware, a number of modulation schemes are available for transmitting data via magnetic coupling. The preferred schemes include but are not limited to amplitude modulation, frequency modulation, frequency shift keying, phase shift keying, and also spread spectrum techniques. The preferred modulation scheme may be determined by the specifications of an individual application, and is not intended to be limited under this invention.

In addition to the many available modulation techniques, there are many technologies developed that allow the implant to communicate back to the reader the signal containing pressure information. It is understood that the reader device may transmit either a continuous level of RF power to supply the implant's needed energy, or it may pulse the power allowing temporary storage in a battery or capacitor device. Similarly, the implant **201** of Fig. 3 may signal back to the reader **202** at any interval in time, delayed or instantaneous, during reader RF (Radio Frequency) transmission or alternately in the absence of reader transmission. The implant **201** may include a single coil antenna **204** for both reception and transmission, or it may include two antennas, one each for transmission **204** and reception **221**. There are many techniques for construction of the reader coil **219** and processing electronics known to those skilled in the art. The reader **202** may interface to a display, computer, or other data logging devices **220**.

The electronic circuit may consist of a receiving inductor coil **204**, rectification circuitry **203**, signal conditioning circuitry **211**, and signal transmission circuitry **212**.

A large number of possible geometries and structures are available for receiver coil and known to those skilled in the art. The coil conductor may be wound around a ferrite core to

enhance magnetic properties, deposited on a flat rigid or flexible substrate, and formed into a long/skinny or short/wide cylindrical solenoid. The conductor is preferably made at least in part with a metal of high conductivity such as copper, silver, gold. The coil may alternately be fabricated on implantable sensor substrates. Methods of fabrication of coils on the sensor substrate include but not limited to one or more or any combination of the following techniques: sputtering, electroplating, lift-off, screen printing, and/or other suitable methods known to those skilled in the art.

The rectification circuitry **203** outputs a constant voltage level for the other electronics from an alternating voltage input. Efficient realizations of such circuitry are standard electronic techniques and may include either full bridge diode rectifiers or half-bridge diode rectifiers in the preferred embodiment. This rectification circuitry may include a capacitor for transient energy storage to reduce the noise ripple on the output supply voltage. This circuitry may be implemented on the same integrated circuit die with other electronics.

The signal conditioning circuit **211** processes an output signal from the sensor **206** and prepares it for transmission to an external receiving and/or analyzing device. For example, many pressure sensors output a capacitance signal that may be digitized for radio frequency (RF) transmission. Accordingly, the signal conditioning circuit **211** places the output signal of the sensor into an appropriate form. Many different signal conditioning circuits are known to those skilled in the art. Capacitance to frequency conversion, sigma delta or other analog to digital conversion techniques are all possible conditioning circuits that may be used in a preferred embodiment.

The signal transmission circuitry **212** transmits the encoded signal from the signal conditioning circuitry for reception by an external reader. Magnetic telemetry is again used for this communication, as the transmission circuitry **212** generates an alternating electromagnetic

field that propagates to the reader **202**. Either the same coil **204** is used for signal reception and for transmission, or alternately a second coil **221** is dedicated for transmission only.

A third option, particularly useful for (but not limited to) situations in which long-term data acquisition without continuous use of the readout unit is desirable, is to implement the sensor using an active scheme. This approach incorporates an additional capacitor, battery, rechargeable battery, or other power-storage element that allows the implant to function without requiring the immediate presence of the readout unit as a power supply. Data may be stored in the sensor and downloaded intermittently using the readout unit as required.

The implantable sensor may be physically realized with a combination of any of several technologies, including those using microfabrication technology such as Microelectromechanical Systems (MEMS). For example, capacitive and piezoresistive pressure sensors have been fabricated with MEMS technology. A hermetic sensor package may be formed from anodically bonded layers of glass and silicon (doped or undoped). Anchoring provisions may be incorporated directly into such a hermetic package, or they may alternately be added with an additional assembly step (e.g. as shown in Figure 4). An example of this would be insertion of the package into a molded plastic or metal shell that incorporates anchoring provisions. Possible anchoring methods include those conventionally used for cardiac pacing leads, such as screws or tines, as well as septal occluder schemes. Many such packaging schemes are known to those familiar with the art, and the present description should not be construed as limiting.

In addition to the basic implant-and-reader system, a number of other embodiments of the technology can be realized to achieve additional functionality. The system may be implemented as a remote monitoring configuration, including but not limited to home monitoring, which may include but not limited to telephone based, wireless communication based, or web-

based (or other communication means) delivery of information received from the implant by the reader to a physician or caregiver.

A closed-loop drug delivery system may also be envisioned. Data from the implanted sensor is fed directly to a drug delivery device (which may or may not be implanted, and may or may not be an integral part of the implanted sensor). This approach would allow continuous adjustment of medications for pulmonary-hypertension-related conditions with minimal physician intervention.

Implanted sensor data may be used as feedback for a RA→LA unidirectional valve, in either an open-loop or closed-loop configuration, which can be used to treat pulmonary hypertension in at-risk patients. For example, the valve could be modulated to maintain a mean RA-LA pressure <10 mmHg. Pulmonary decompression is accomplished by allowing some blood to flow directly between the RA and LA, thus reducing the PA pressure.

The implantable sensor can be any suitable miniature sensor adapted to detect and/or monitor various physiological parameters. For example, the sensor can comprise a pressure sensor, a temperature sensor, a flow sensor, a velocity sensor, or a sensor adapted to measure specific chemistries such as gas content (e.g., O2 and CO2) and glucose levels. Various specific examples of these types of miniature sensors are known to those skilled in the art, and any one or more of these suitable sensors can be utilized in the sensor module of the present invention. While the specific type of sensor(s) chosen will depend on the application of the implantable system, the sensor(s) should be of a sufficiently small size in order to facilitate placement within a catheter for delivery and implantation.

To limit the risk of thrombogenesis, the preferred embodiment has limited protrusion of volume into the blood stream (particularly in the left side of the heart), as both shape and size are factors in thrombogenesis. Another shell may be overmolded or preformed to house the glass/silicon module, and the outer shell contains the necessary apparatus for anchoring the

implant. In a preferred embodiment, the outer shell may be formed with existing plastic injection technologies suitable for medical implantation. A coating, preferably of silicone, parylene and/or polymers provides a non-thrombogenic exterior for the biologic environment.

The implant may be located in various places depending on the blood pressure measurement of interest. Because the number of implants is not practically limited by the technology, multiple locations for blood pressure and/or other physiologic parameter measurements are easily established, including all chambers of the heart, major arteries and appendages. The atrial septum is a preferred embodiment, Figure 5, since, embedding the module in the atrial septum does not significantly impede blood flow and thus minimize the thrombogenic effect of flow turbulence caused by this volume.

The implant may be modified with anchoring methods found on devices already used for implantation. Devices such as septal occluders, pacemaker leads, left atrial appendage occluders, etc., may be used as carriers for the current invention. Devices have been made and approved by the FDA to occlude atrial septum defects (a septal occluder) and other vascular holes. An umbrella structure **14,** Figure 5, may be folded inside a catheter for delivery and then expanded for implantation. In a preferred embodiment, the present invention may be anchored to the septum with similar techniques, as shown in Figure 5. An important aspect of this preferred embodiment is that the majority of the implantable sensing device is located in the right side of the heart, with minimum protrusion in the left side of the heart. This embodiment will greatly reduce the thrombogenicity.

Pacemaker leads have a well-established history for implantation methods, and similar techniques are possible for the current invention. A screw **13** (Figure 4) or barb may be used to attach the implant to a heart or vessel wall. In the first package option shown in Figure 4, a screw **13** may be molded into the device shell **26**, and screwed into the ventricle wall so that

that the screw buries below the wall surface. In addition, the package may have mesh **25** attached to the device to promote tissue growth and anchoring.

A second package option can be attached with a metal tine or barb placed with a catheter. These devices work well in tribeculated areas of the heart, and therefore are used often for implanting pacing leads in the right ventricle. Clips or expanding probes may also be used, both of which would penetrate the heart or vessel wall slightly.

Devices have been made and approved by the FDA to occlude atrial septum defects (a septal occluder) and other vascular holes. An umbrella structure may be folded inside a catheter for delivery and then expanded for implantation, shown Figure 5. In the preferred embodiment, the present invention is anchored to the septum with similar techniques. An important aspect of this preferred embodiment is that the majority of the implantable sensing device is located in the right side of the heart, with minimum protrusion in the left side of the heart. This embodiment will greatly reduce the thrombogenicity.

In another preferred embodiment for anchoring the implantable sensing unit, an implantable unit with a small diameter (less than 5 mm) is injected into a large pulmonary artery, the blood flow pushes the implant through one or more pulmonary arteries with smaller diameters than the diameter of the large artery used for the injection, until the implantable sensors goes into a pulmonary artery that is small enough to prevent further moving of the implantable sensor unit. The implantable sensor unit is now anchored in this pulmonary artery. As cell growth and encapsulation happens over time, further stabilization of the implantable sensor is achieved. In this approach, the PA that is used for anchoring the sensor is blocked; however, there are many more pulmonary arteries that will compensate for this blocked PA. The implantable sensing unit is designed to operate while there is a layer of cell growth on top of it.

Note that in addition to sensing physiologic parameters, the described system could be augmented with various actuation functions. In such case, the implant device would be augmented with any of various actuators, including but not limited to: thermal generators; voltage or current sources, probes, or electrodes; drug delivery pumps, valves, or meters; microtools for localized surgical procedures; radiation-emitting sources; defibrillators; muscle stimulators; pacing stimulators, left ventricular assisting device (LVAD).

The foregoing disclosure includes the best mode devised by the inventors for practicing the invention. It is apparent, however, that several variations in the apparatuses and methods of the present invention may be conceivable by one skilled in the art. Inasmuch as the foregoing disclosure is intended to enable one skilled in the pertinent art to practice the instant invention, it should not be construed to be limited thereby, but should be construed to include such aforementioned variations.